Overview of Generation IV Technology Roadmap

Generation IV Technology Goals

Six Generation IV systems have been selected by the Generation IV International Forum (GIF) countries to meet challenging technology goals in four areas:

- Sustainability
- Economics
- Safety and reliability
- Proliferation resistance and physical protection.

By striving to meet the technology goals, new nuclear systems can achieve a number of long-term benefits that will help nuclear energy play an essential role worldwide.

Sustainable Nuclear Energy

Sustainability is the ability to meet the needs of the present generation while enhancing the ability of future generations to meet society's needs indefinitely into the future. The benefits of meeting sustainability goals include:

- Having a positive impact on the environment through the displacement of polluting energy and transportation sources by nuclear electricity generation and nuclear-produced hydrogen
- Allowing geologic waste repositories to accept the waste of many more plant-years of nuclear plant operation through substantial reduction in the amount of wastes and their decay heat
- Greatly simplifying the scientific analysis and demonstration of safe repository performance for very long time periods (beyond 1000 years), by a large reduction in the lifetime and toxicity of the residual radioactive wastes sent to repositories for final geologic disposal
- Extending the nuclear fuel supply into future centuries by recycling used fuel to recover its energy content, and by converting ^{238}U to new fuel.

Competitive Nuclear Energy

Economics goals broadly consider competitive costs and financial risks of nuclear energy systems. The benefits of meeting economics goals include:

- Achieving economic life-cycle and energy production costs through a number of innovative advances in plant and fuel cycle efficiency, design simplifications, and plant sizes
- Reducing economic risk to nuclear projects through innovative advances that may be possible with the development of plants built using innovative fabrication and construction techniques, and modular plants
- Allowing the distributed production of hydrogen, fresh water, district heating, and other energy products to be produced where they are needed.

Safe and Reliable Systems

Safe and reliable operation of nuclear systems is an essential priority in the development of next-generation systems. Safety and reliability goals broadly consider safe and reliable operation, improved accident management and minimization of consequences, investment protection, and reduced need for off-site emergency response. The benefit of meeting these goals includes:

- Increasing the use of inherent safety features, robust designs, and transparent safety features that can be understood by nonexperts
- Enhancing public confidence in the safety of nuclear energy.

Proliferation Resistance and Physical Protection

Proliferation resistance and physical protection consider means for safeguarding nuclear material and nuclear facilities. The benefits of meeting these goals include:

- Providing continued effective proliferation resistance of nuclear energy systems through the increased use of intrinsic barriers and extrinsic safeguards
- Increasing physical protection against terrorism by increasing the robustness of new facilities.

Generation IV Nuclear Energy Systems

Generation IV nuclear energy systems comprise the nuclear reactor and its energy conversion systems, as well as the necessary facilities for the entire fuel cycle, from ore extraction to final waste disposal. The following six systems, listed alphabetically, were selected to Generation IV by the GIF:

Generation IV System	Acronym
Gas-Cooled Fast Reactor System	GFR
Lead-Cooled Fast Reactor System	LFR
Molten Salt Reactor System	MSR
Sodium-Cooled Fast Reactor System	SFR
Supercritical-Water-Cooled Reactor System	SCWR
Very-High-Temperature Reactor System	VHTR

The motivation for the selection of six systems is to:

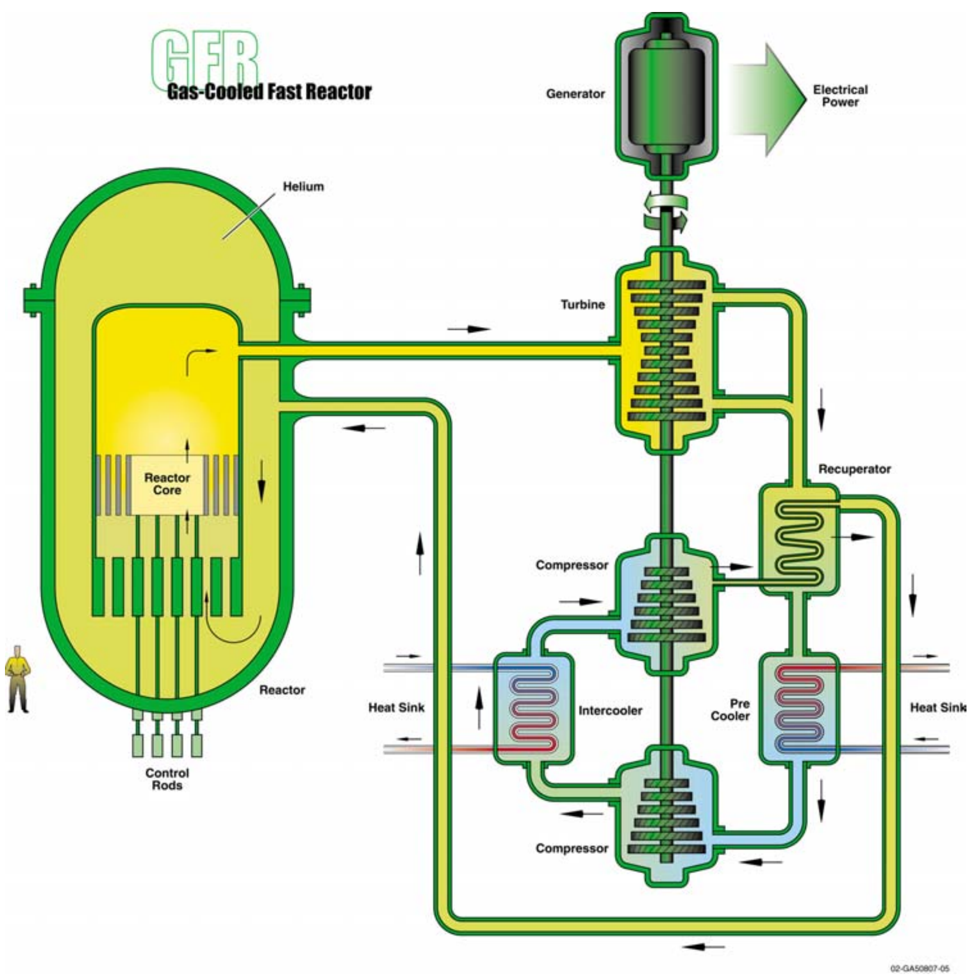
- Identify systems that make significant advances toward the technology goals
- Ensure that the important missions of electricity generation, hydrogen and process heat production, and management of actinides may be adequately addressed by next-generation systems
- Provide some overlapping coverage of capabilities, because not all of the systems may ultimately be viable or attain their performance objectives and achieve commercial deployment
- Accommodate the range of national priorities and interests of the GIF countries.

Each Generation IV system is described briefly.

GFR – Gas-Cooled Fast Reactor System

The GFR system features a fast-neutron-spectrum helium-cooled reactor [shown below] and closed fuel cycle. Like thermal-spectrum helium-cooled reactors, the high outlet temperature of the helium coolant makes it possible to deliver electricity, hydrogen, or process heat with high efficiency. The reference reactor is a 288-MWe helium-cooled system operating with an outlet temperature of 850°C using a direct Brayton cycle gas turbine for high thermal efficiency. Several fuel forms are candidates that hold the potential to operate at very high temperatures and to ensure an excellent retention of fission products: composite ceramic fuel, advanced fuel particles, or ceramic clad elements of actinide compounds. Core configurations may be based on prismatic blocks, pin- or plate-based fuel assemblies. The GFR reference has an integrated, on-site spent fuel treatment and refabrication plant.

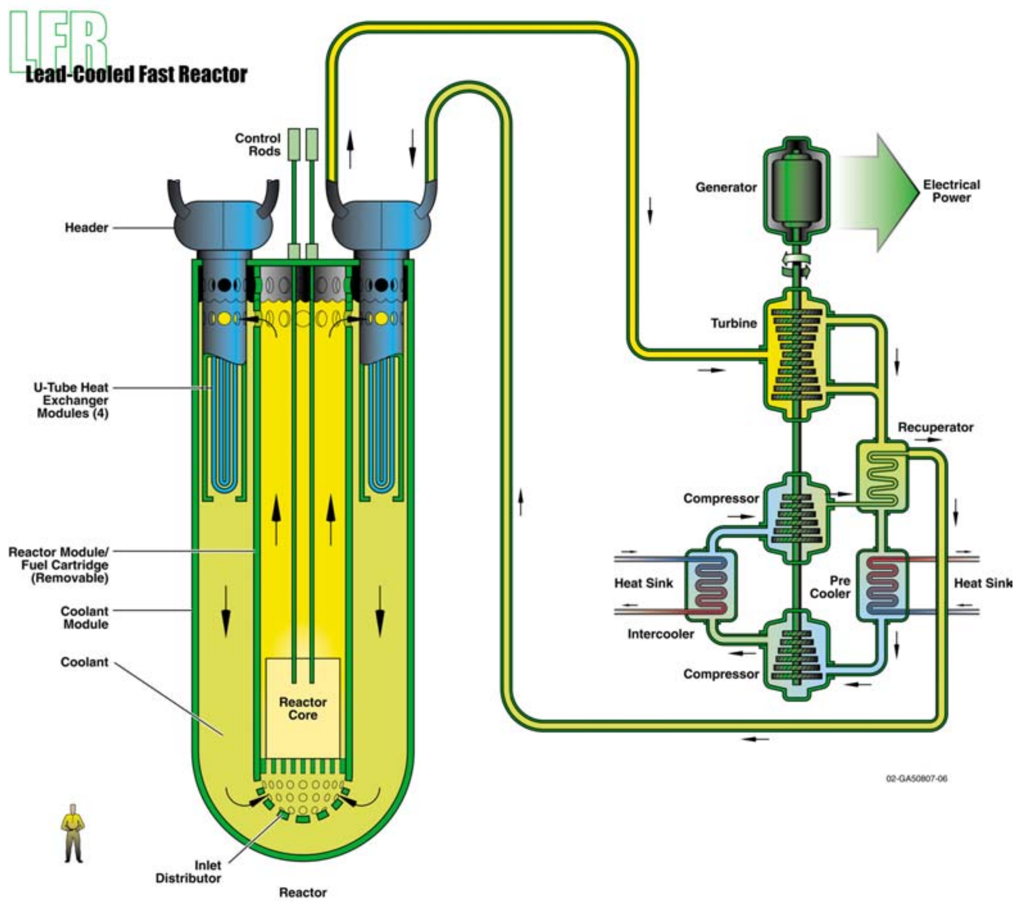
The GFR uses a direct-cycle helium turbine for electricity generation, or can optionally use its process heat for thermochemical production of hydrogen. Through the combination of a fast spectrum and full recycle of actinides, the GFR minimizes the production of long-lived radioactive waste. The GFR's fast spectrum also makes it possible to utilize available fissile and fertile materials (including depleted uranium) considerably more efficiently than thermal spectrum gas reactors with once-through fuel cycles.



LFR – Lead-Cooled Fast Reactor System

The LFR system features a fast-spectrum lead or lead/bismuth eutectic liquid metal-cooled reactor and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides. The system has a full actinide recycle fuel cycle with central or regional fuel cycle facilities. Options include a range of plant ratings, including a battery of 50-150 MWe [shown below] that features a very long refueling interval, a modular system rated at 300-400 MWe, and a large monolithic plant option at 1200 MWe. The term *battery* refers to the long-life, factory fabricated core, not to any provision for electrochemical energy conversion. The fuel is metal or nitride-based, containing fertile uranium and transuranics. The LFR is cooled by natural convection with a reactor outlet coolant temperature of 550°C, possibly ranging up to 800°C with advanced materials. The higher temperature enables the production of hydrogen by thermochemical processes.

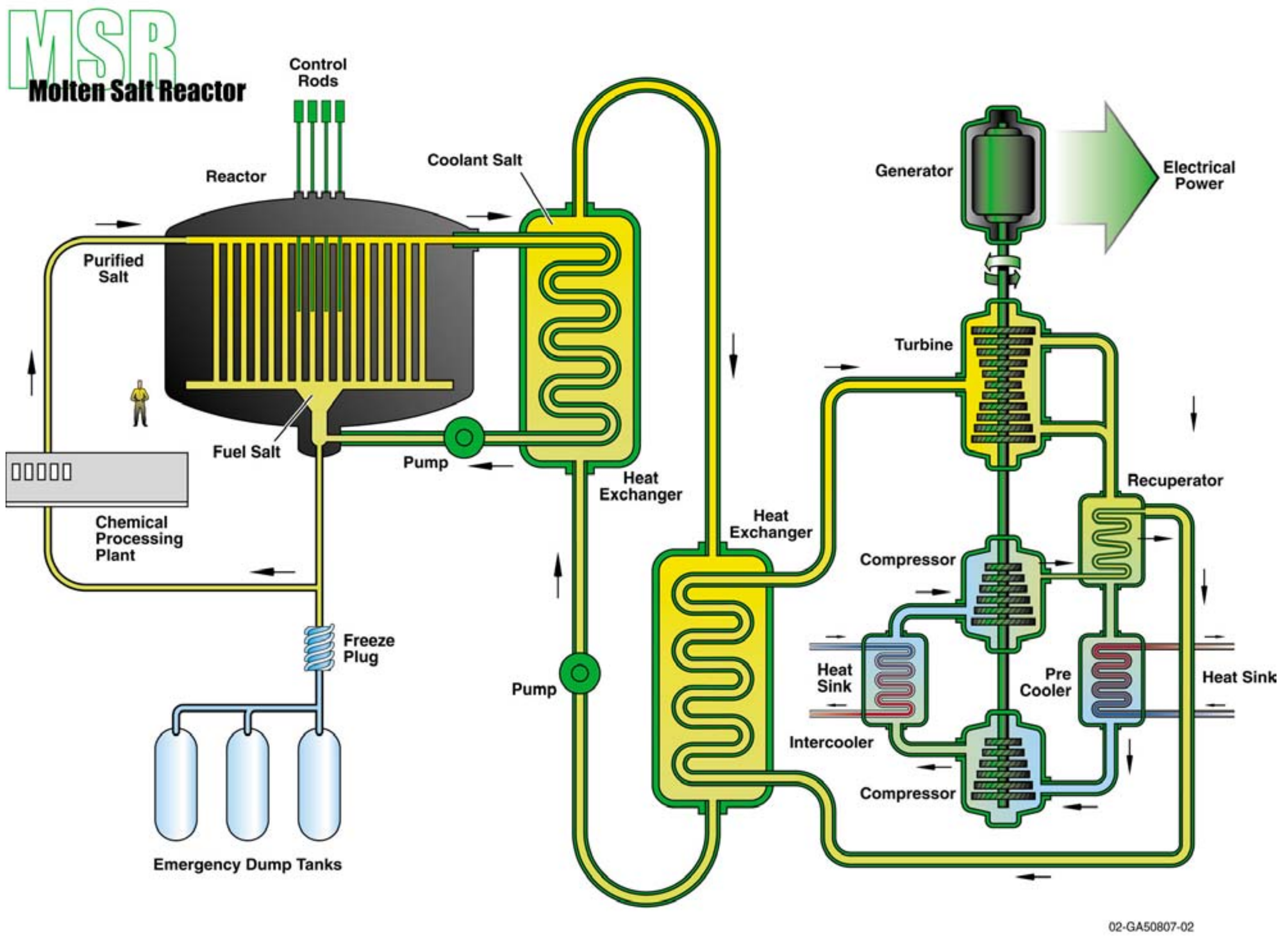
The LFR battery is a small factory-built turnkey plant operating on a closed fuel cycle with very long refueling interval (15 to 20 years) cassette core or replaceable reactor module. Its features are designed to meet market opportunities for electricity production on small grids, and for developing countries that may not wish to deploy an indigenous fuel cycle infrastructure to support their nuclear energy systems. The battery system is designed for distributed generation of electricity and other energy products, including hydrogen and potable water.



MSR – Molten Salt Reactor System

The MSR system produces fission power in a circulating molten salt fuel mixture with an epithermal-spectrum reactor [shown below] and a full actinide recycle fuel cycle. In the MSR system, the fuel is a circulating liquid mixture of sodium, zirconium and uranium fluorides. The molten salt fuel flows through graphite core channels, producing an epithermal spectrum. The heat generated in the molten salt is transferred to a secondary coolant system through an intermediate heat exchanger, and then through a tertiary heat exchanger to the power conversion system. The reference plant has a power level of 1000 MWe. The system has a coolant outlet temperature of 700°C, possibly ranging up to 800°C, affording improved thermal efficiency.

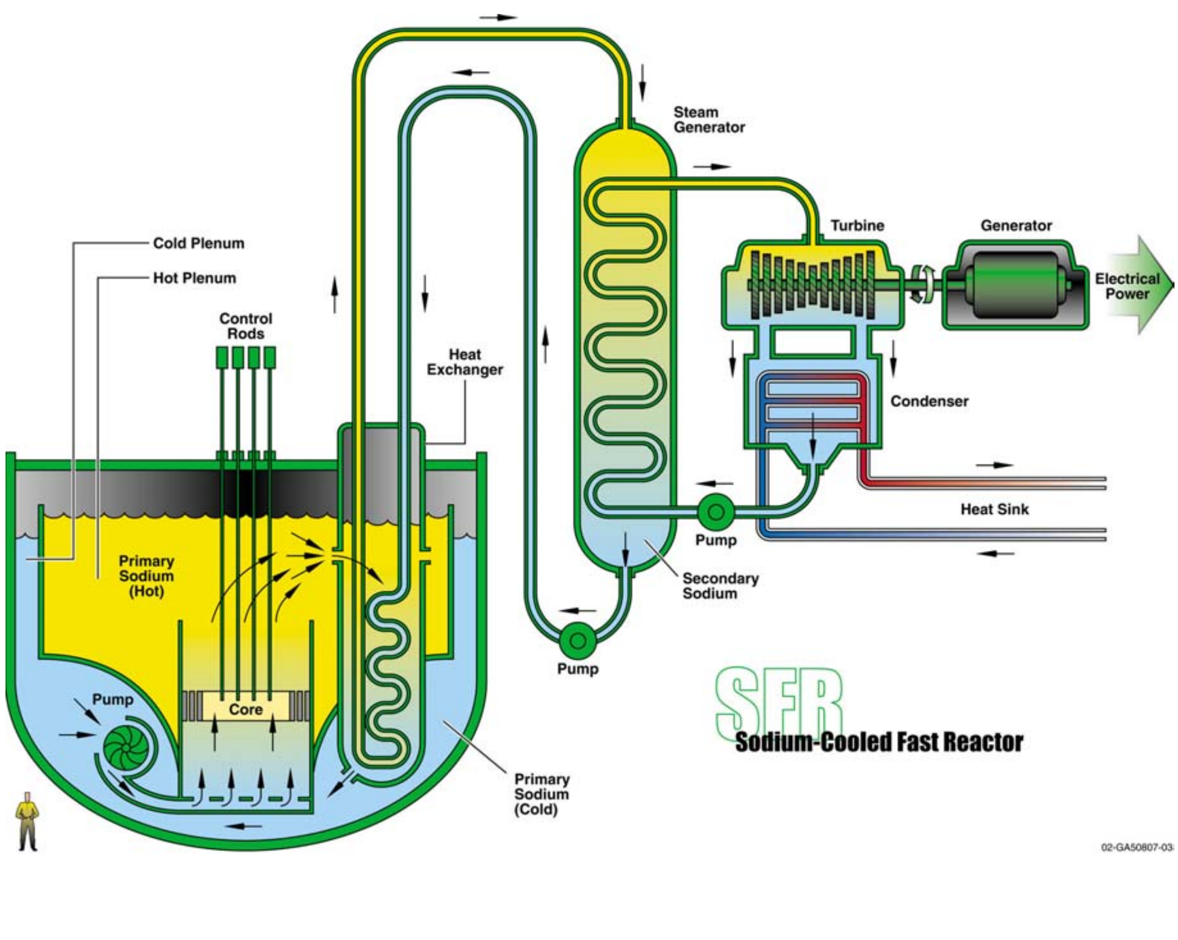
The closed fuel cycle can be tailored to the efficient burnup of plutonium and minor actinides. The MSR's liquid fuel allows addition of actinides such as plutonium and avoids the need for fuel fabrication. Actinides and most fission products form fluorides in the liquid coolant. Molten fluoride salts have excellent heat transfer characteristics and a very low vapor pressure, which reduce stresses on the vessel and piping.



SFR – Sodium-Cooled Fast Reactor System

The SFR system features a fast-spectrum sodium-cooled reactor [shown below] and a closed fuel cycle for efficient management of actinides and conversion of fertile uranium. The fuel cycle employs full actinide recycle with two major options: One is an intermediate size (150 to 500 MWe) sodium-cooled reactor with a uranium-plutonium-minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in facilities integrated with the reactor. The second is a medium to large (500 to 1500 MWe) sodium-cooled reactor with mixed uranium-plutonium oxide fuel, supported by a fuel cycle based upon advanced aqueous processing at a central location serving a number of reactors. The outlet temperature is approximately 550°C for both.

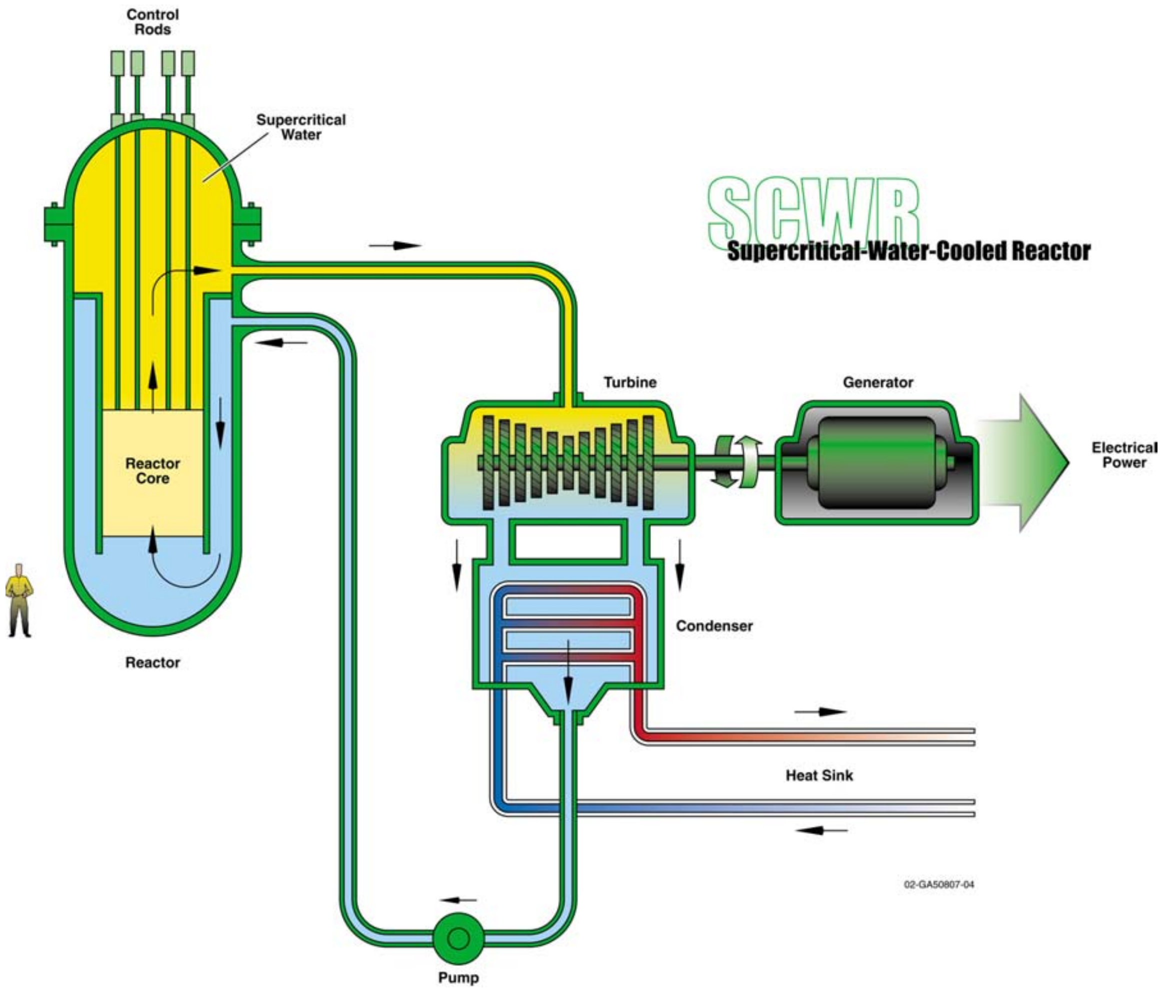
The SFR is designed for management of high-level wastes and, in particular, management of plutonium and other actinides. Important safety features of the system include a long thermal response time, a large margin to coolant boiling, a primary system that operates near atmospheric pressure, and an intermediate sodium system between the radioactive sodium in the primary system and the water and steam in the power plant. With innovations to reduce capital cost, the SFR can serve markets for electricity. The SFR's fast spectrum also makes it possible to utilize available fissile and fertile materials (including depleted uranium) considerably more efficiently than thermal spectrum reactors with once-through fuel cycles.



SCWR – Supercritical-Water-Cooled Reactor System

The SCWR system is a high-temperature, high-pressure water-cooled reactor [shown below] that operates above the thermodynamic critical point of water (374°C, 22.1 MPa or 705°F, 3208 psia). The supercritical water coolant enables a thermal efficiency about one-third higher than current light water reactors, as well as simplifications in the balance of plant. The balance of plant is considerably simplified because the coolant does not change phase in the reactor and is directly coupled to the energy conversion equipment. The reference system is 1700 MWe with an operating pressure of 25 MPa, and a reactor outlet temperature of 510°C, possibly ranging up to 550°C. The fuel is uranium oxide. Passive safety features are incorporated similar to those of simplified boiling water reactors.

The SCWR system is primarily designed for efficient electricity production, with an option for actinide management based on two options in the core design: the SCWR may have a thermal or fast-spectrum. Thus, the system offers two fuel cycle options: the first is an open cycle with a thermal-spectrum reactor; the second is a closed cycle with a fast- spectrum reactor and full actinide recycle based on advanced aqueous processing at a central location.



VHTR – Very-High-Temperature Reactor System

The VHTR is a graphite-moderated, helium-cooled reactor [shown below] with a once-through uranium fuel cycle. It supplies heat with core outlet temperatures of 1000^{o}C, which enables applications such as hydrogen production or process heat for the petrochemical industry or others. The reference reactor is a 600 MWth core connected to an intermediate heat exchanger to deliver process heat. The reactor core can be a prismatic block core such as the operating Japanese HTTR, or a pebble-bed core such as the operating Chinese HTR-10. For hydrogen production, the system supplies heat that could be used efficiently by the thermochemical iodine-sulfur process.

The VHTR system is designed to be a high-efficiency system that can supply process heat to a broad spectrum of high-temperature and energy-intensive, nonelectric processes. The system may incorporate electricity generating equipment to meet cogeneration needs. The system also has the flexibility to adopt U/Pu fuel cycles and offer enhanced waste minimization. Thus, the VHTR offers a broad range of process heat applications and an option for high efficiency electricity production, while retaining the desirable safety characteristics offered by modular high-temperature gas-cooled reactors.